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Short Communication

A probable tyrannosaurid track from the Upper Cretaceous of Southern China

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A large number of Upper Cretaceous (Maastrichtian) dinosaur skeletal fossils have been found in the Nanxiong Basin and adjacent Ganzhou area, including those of theropods, sauropods and hadrosaurids. However, known dinosaur ichnoassemblages from the Nanxiong Basin partly indicate a different fauna, with dominating large- and medium-sized ornithopods, theropods, and pterosaurs [1, 2]. This is one of many known examples where trace and body fossil assemblages from the same formation or geologically discrete region show a different composition. Palecological and paleobiogeographical analyses therefore should consider data from both, before any conclusions can be drawn. Formations can be classified according to the relative degree of similarity or congruity (or difference / incongruity) between trace and body fossils into the 5 categories proposed by Lockley [3]. Type 1 contains only tracks, and Type 5 only body fossils. Intermediate categories 2–4 are tracks > bones, tracks = bones, and tracks < bones, where ichnofossils dominate, are equal or minor in abundance relative to the bone record. Additionally, Lockley [3] introduced the sub-categories a and b, indicating whether the trace and body fossil evidence is largely consistent (a) or not (b). The Nanxiong Basin deposits would fall in the category 4b, means bones > tracks, but representing different faunal groups.

In March 2019, the Yingliang Stone Nature History Museum collected a large tridactyl track from the Hekou Formation (Guifeng Group, Upper Cretaceous) of Zhanggong District in Gan County, Ganzhou City, Jiangxi Province. It was slightly damaged during collection, but basically complete. This is the first dinosaur track found in the Ganzhou area. The large size of the track is suggestive of a large theropod trackmaker, potentially similar to the Ganzhou genus *Qianzhousaurus* [4], which was found in the same formation at a site about 33 km away.

The new material is preserved as a convex hyporelief and comes from the Zhanggong tracksite. It was designated YLSNHM01130 (YLSNHM = Yingliang Stone Nature History Museum, Shuitou, China) (Fig. 1). The track-bearing Hekou Formation extends to Nanxiong in Guangdong Province, and is comparable to the Dafeng/Yuanpu formations in the lower section of the Nanxiong Formation (Supplementary Materials).

Identification of an isolated tridactyl track as a left or right pes imprint is not always easy, especially in poorly preserved specimens. Generally, in well-preserved theropod tracks there are asymmetries between digit traces II and IV, and there is a postero-medial notch behind the digit II trace near the heel. Also, the digit IV trace has a larger number of phalangeal pads and is more slender when compared to digit II. Very often, there is a slight or quite marked inward curvature of the middle digit (digit III) trace. Evident and sharp claw marks as well as a posterior-medial notch, usually considered diagnostic of a theropod trackmaker, can be seen in YLSNHM01130. Based on the above characteristics, YLSNHM01130 can be identified as a right footprint cast.

YLSNHM01130 is 58 cm in length and 47 cm in width, with a length/width ratio of 1.2, and a divarication angle between digits II and IV of 61°. The divarication angle between digits II and III (35°) is larger than between digits III and IV (26°), which is a characteristic feature of theropod tracks. The mesaxony (the degree to which digit III protrudes anteriorly beyond digits II and IV) is 0.41. The digit impressions of YLSNHM01130 are wide and lack obvious digital pad impressions. The terminal claw marks are sharp, and especially digits II and III, with the distal part of digit III show strong inward curvature. Digit traces are thick proximally and taper strongly distally. The heel is highly developed without a distinct boundary with the digital area. It is shallower than the digit impressions, which may indicate an anteriorly shifted center of gravity due to the high walking speed of the trackmaker, or simply reflect the greater penetration of the substrate by the distal portion of digits. At the postero-medial margin, posterior to the trace of digit II, two elevated areas of the cast are visible, which include a distally tapering ridge. This ridge could represent a poorly preserved hallux (digit I) trace, but this interpretation is uncertain.

Compared with their skeletal fossils, the footprints of tyrannosaurids are even scarcer (Fig. 2). *Tyrannosauropus petersoni* was re-assigned to hadrosaur tracks due to the geologic age and morphological differences [5]. Lockley et al. [6] reviewed other possible tyrannosaurid tracks with their geologic age and potentially diagnostic morphological features. Generally, all are from Maastrichtian deposits of North America and represent typical large theropod type tracks. Many of the documented tyrannosaurid tracks have been tentatively attributed to *Tyrannosaurus rex*, and these include: (1) a possible *Tyrannosaurus* track from the Laramie Formation of Golden, Colorado [6]; (2) *Tyrannosauripus pilmorei* from the Raton Formation, near Cimarron, New Mexico [5], which is the most reliable *T. rex* track [6]; (3) a poorly preserved track from the Lance Formation of Wyoming [7]; (4) a probable tyrannosaurid track from the Hell Creek Formation of Montana [8]; and (5) a short trackway from the Lance Formation of Wyoming [9]. Their mesaxony values range from 0.27 to 0.64, and all are similar to the 0.41 value calculated for YLSNHM01130, except the specimens from Colorado and Montana.

Beyond those likely pertaining to *T. rex*, itself, a handful of additional tyrannosaurid tracks have been reported. McCrea et al. [10] documented the first tyrannosaurid trackways, and named the new species *Bellatoripes fredlundi*, which comes from the Wapiti Formation (Campanian–Maastrichtian) of British Columbia, Canada [10]. Lockley et al. [11] introduced a new ichnotaxon *Wakinyantanka styxi*, based on a large theropod trackway from the Hell Creek Formation of South Dakota, together with similar morphotypes from Utah, from Colorado and from Europe (Poland). In contrast to other known tyrannosaurid tracks, they shows less robust digits, and therefore may belong to a more gracile, smaller form such as *Nanotyrannus* or some albertosaurines, or be no tyrannosaur tracks at all [11]. Currie et al. [12] mentioned a large (track length ~68.6 cm) tridactyl track, MPD 100F/12, with narrow digits, small interdigital angles, and more pointed claws, from the Upper Cretaceous Nemegt Formation, in the Gobi Desert of Mongolia. Stettner et al. [13] also documented a large (length > 55 cm) tridactyl theropod track from the Gobi site FS03. These Gobi tracks are definitively those of large non-deinocheirid and non-therizinosaur theropods, and the only such theropods known from Nemegt are tyrannosaurids, such as *Alioramus* and *Tarbosaurus*. These records are not described in detail, but their morphological characteristics are very similar to tracks of the Tyrannosauripodidae ichnofamily.

Morphologically, YLSNHM01130 is different from other large theropod tracks from China (Supplementary Materials) but similar to the well-preserved *Tyrannosauripus* tracks from New Mexico [5] and to *Bellatoripes* from British Columbia [10]). All are large, robust, functionally tridactyl and mesaxonic, have distal metatarsal pad impressions, a length greater than width, thick digit traces, wide divarication, a well-developed digit II, digits with evident claw marks, and a large heel. Additionally, the tracks all lack distinct digital pad impressions, without clear boundaries between the three digits. Note also that, in the Nanxiong example, the digit II trace is broad and fleshy, as in *Tyrannosauripus*, there is a notch posterior to digit II where the possible hallux trace is situated, and digit IV is more elongate and narrow [5]. Therefore, it is reasonable to refer YLSNHM01130 to Tyrannosauripodidae [10], and it is here tentatively assigned to *Tyrannosauripus* isp.

The hip height of the trackmaker is generally calculated by being four times the length of the foot, that is, foot length × the conversion factor (4), while the coefficient of large theropods with feet longer than 0.25 m is 4.9 [14]. Xing et al. [15] suggested that the ratio of hip height to body length of theropods should be about 1:2.63, making the body length of YLSNHM01130 trackmaker at least 7.5 m. This is generally similar to the estimated length of the *Qianzhousaurus* holotype skeleton which was probably approximately 7.5 to 9 meters long, according to calculations by Junchang Lü during his study of the material with SLB. Unfortunately the holotype specimen preserves very limited metatarsal and phalangeal remains, which makes it difficult to estimate foot length and width. Nevertheless, it is clear that the footprint we describe here is comparable in overall size to the foot of the *Qianzhousaurus* holotype individual (SLB pers. obs.).

The large theropod track (length 58 cm) here described, from Maastrichtian deposits of the Nanxiong Basin, is best attributed to a tyrannosaurid, probably an animal roughly the size of *Qianzhousaurus,* which is possibly the trackmaker based on the current body-fossil record of the region. The Nanxiong Basin deposits are considered Type 4b, where bones are more common than tracks, but with different faunal components of the latter. The *Qianzhousaurus*-like theropod track is an exception to this pattern and highlights the need to consider both tracks and body fossils for a complete picture of the fauna. In future, footprint data will challenge conclusions from the skeletal record, for example if there was truly an abnormal abundance and diversity of oviraptorosaurs, as indicated by the body fossils.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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Author contributions

Lida Xing conceived and designed the experiments. Lida Xing and Anthony Romilio performed the experiments. Lida Xing, Martin G. Lockley and Anthony Romilio analyzed the data. Lida Xing, Martin G. Lockley, Hendrik Klein, W. Scott Persons IV and Stephen L. Brusatte wrote the paper. Kecheng Niu support and research site access.

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Captions

Fig. 1, Photograph (a), 3D height image (warm colors = high areas, cool colors = low areas) (b) and interpretive outline drawing (c), gray area represents the damaged parts) of tyrannosaurid track from the Upper Cretaceous Hekou Formation, Jiangxi, China.

Fig. 2, Upper Cretaceous tyrannosaurid tracks from Asia and North America. (a) Possible *Tyrannosaurus* track from the Laramie Formation of Golden, Colorado [6]; (b) *Tyrannosauripus pilmorei* from the Raton Formation, near Cimarron, New Mexico [5]; (c) poorly preserved track possibly attributable to *Tyrannosaurus* from the Lance Formation of Wyoming [7]; (d) probable tyrannosaurid track from the Hell Creek Formation of Montana [8]; (e)–(g): tyrannosaurid track *Bellatoripes fredlundi* from the Wapiti Formation (Campanian–Maastrichtian) of British Columbia, Canada[10]; h: tyrannosaurid track from Jiangxi (this text)

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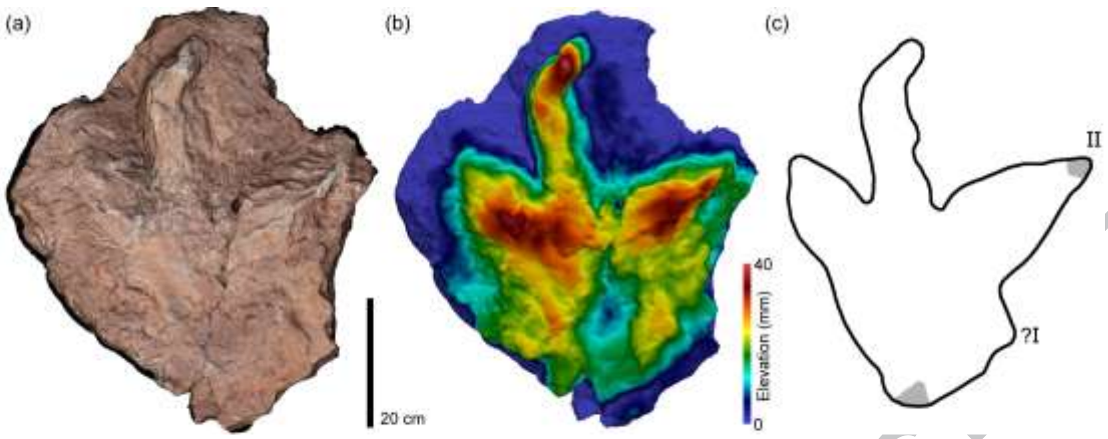
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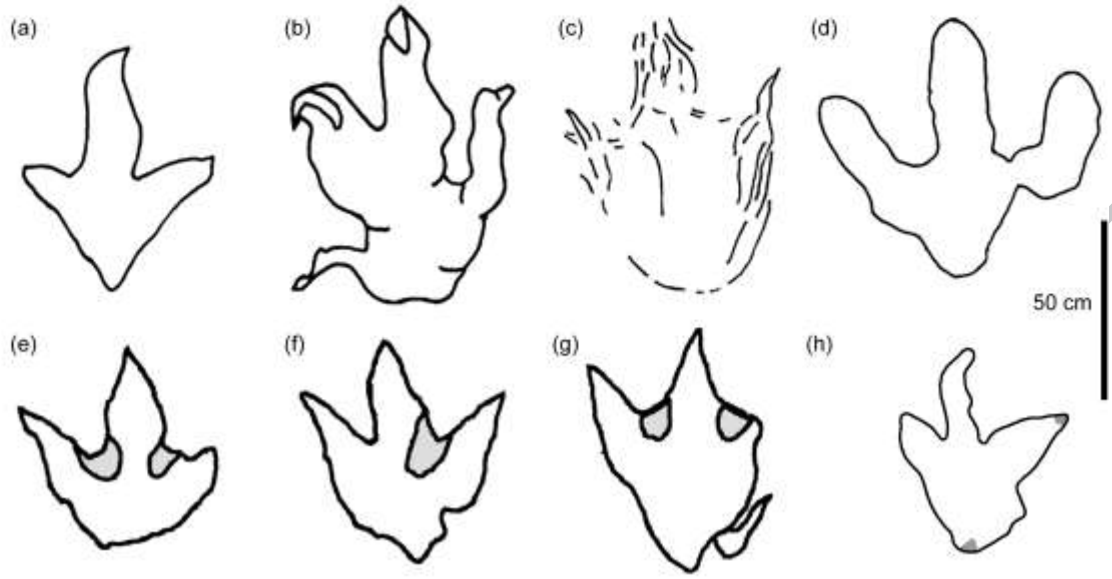
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